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Technical Report

PERMEABILITY STUDIES OF REINFORCED THIN-SHELL CONCRETE

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PERMEABILITY STUDIES OF REINFORCED THIN-SHELL CONCRETE

Technical Report R-692

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by

John R. Keeton

ABSTRACT

Falling-head permeability tests were conducted on specimens of two normal-weight concretes and two lightweight concretes typical of those used in thin-shell reinforced concrete roofs. Specimens of each concrete with galvanized mesh reinforcement were tested in thicknesses of 1 inch, 2 inches, and 4 inches. Initially, the upper face of each specimen was exposed to a 20-inch head of water. The lower faces of the specimens were initially exposed to relative humidities of 25%, 50%, 70%, or 100%, all at a constant temperature of 73.4^{o}F. A lightweight concrete utilizing expanded shale for both coarse and fine aggregate was the least permeable of all the concretes tested. The degree of zinc oxidation from the mesh was determined for some of the specimens. The reliability of the equation for coefficient of permeability (falling head) could not be verified. Any of the concretes tested in this study could be used to make a relatively impermeable thin-shell concrete roof. Since the concrete itself can be made satisfactorily resistant to water passage, cracks are the most significant source of water leakage through thin-shell concrete roofs.

CONTENTS

BACKGROUND

Possibly the greatest deterrent to general acceptance of thin-shell concrete roof construction is the difficulty encountered in obtaining and maintaining satisfactory weather-resistant surfaces.[1] In 1961 the Building Research Institute (BRI) organized a workshop—conference on weatherproofing thin-shell concrete roofs. The workshop participants, drawn from all appropriate branches of the construction industry and its related professions, were to determine the best practices for weatherproofing shell roofs and to define problems requiring additional research and development.[2] At the close of the workshop, many technical problems remained unsolved with respect to weatherproofing coatings; in fact, the BRI group felt that the problems themselves were not well defined.[1,2]

Studies in this work unit at the Naval Civil Engineering Laboratory were intended to extend knowledge of the degree to which concrete resists penetration by water. After determination of permeability factors for various concrete specimens, it was planned to investigate means of increasing the resistance of the same specimens to passage of water. Because establishing the permeability characteristics of concrete is a lengthy process, this latter goal was only partially realized in the time span allotted for the study.

To make the study as practical as possible, two normal-weight and two lightweight concretes were investigated. All concrete specimens incorporated 2 x 2-inch galvanized steel mesh as reinforcing. This provided an opportunity to observe the effects of the highly alkaline concrete environment on the zinc coating of the mesh.

INTRODUCTION

Understanding the resistance of concrete to the passage of water through it requires a familiarization with the basic nature of the concrete itself, for which the reader is referred to References 3, 4, and 5. Fundamentally, concrete is a mixture of cement paste (portland cement and water) and inert particles (aggregate). Hardened cement paste consists of cement

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INTRODUCTION

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gel (containing gel pores), capillary pores, air voids, and water. The cement gel is a hygroscopic solid with enormous specific surface area which envelopes a large number of very small voids called gel pores.

Aggregates

The predominant component of concrete is aggregate, composed of relatively inert mineral particles, constituting about 75% of the volume of concrete. The volume occupied by compacted concrete is slightly larger than the compacted volume of the aggregate it contains. The increase in volume reveals that the aggregate particles are not necessarily in contact with each other. The fact is, freshly mixed concrete can have plasticity only if the aggregate particles are dispersed to some extent in the paste. In addition, examination of broken concrete reveals that some degree of dispersion remains after the concrete hardens.

The plastic matrix in which the aggregate particles are dispersed is composed of cement paste (cement and water) and air bubbles. The proportion and size of the air bubbles are dependent upon the consistency of the paste, the gradation of the aggregate, and whether or not air was purposely entrained as a part of the mix design.

Passage of Water Through Concrete

Strictly speaking, there is no clear-cut definition for the term "permeability of concrete." The American Concrete Institute has a definition for "coefficient of permeability to water."* The Bureau of Reclamation Concrete Manual uses the terms "watertightness" and "permeability" interchangeably to mean the relative ease with which water passes (or does not pass) through concrete.[7] The American Society for Testing and Materials refers to a test called "Water Vapor Transmission of Materials in Sheet Form."[8] Griffin and Henry[9,10] have shown that although water may enter or leave concrete as a vapor, it does not move through concrete as a vapor. They also found that the ASTM equation for water vapor transmission through concrete could not be verified by their experimental data. A general conclusion may be that a pertinent measurement of permeability of a given concrete can be obtained only in reference to another concrete.

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* The American Concrete Institute defines the coefficient of permeability to water as: The rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions (usually 20°C).[6]

The conditions of the test determine the value and usefulness of the data. For example, if one is interested in studying permeability of concretes used in thin-shell roofs, there is no reason to use a high-pressure permeability test similar to one which might be used to study the permeability of concrete to be used in a dam. In addition, it would be unrealistic to limit exposure conditions to 100% RH on both sides of the specimen, since it is known that the inside surface of a roof will usually be exposed to a lower humidity and to a more or less stabilized temperature due to air conditioning and heating. The author feels that permeability can best be defined as "the relative ability of the concrete to resist the passage of water in any form."

The data in this report have meaning only for the specific concretes used in this study; however, general trends can be observed for the types of concretes represented.

Since the aggregate particles are surrounded by hardened cement paste, the permeability of a concrete mass is principally a function of the permeability of the hardened cement paste. To pass through concrete, water in any and all forms must pass through pores in the cement paste portion, regardless of the relative porosity or permeability of the aggregate. Water can travel through hardened cement paste only via the pore system. This means that permeability is a function of the volume, size, and continuity of the pores. Due to the larger size of the capillaries (compared to gel pores), water movement is much easier through them. With a low water/cement ratio, W/C, (0.40 or 0.50) however, the capillaries become discontinuous in 14 days or less, leaving the interconnected gel pores as the only continuous phase through which water can pass.

When concrete is completely saturated, water surfaces are continuous throughout. As the concrete begins to dry, however, water is removed by evaporative forces from the capillaries nearest the drying surfaces and then, at a much slower rate, from the gel pores. Almost all capillary water is evaporable at humidities less than 40%.[3] As the gel pores lose water, the films of water remaining become thinner and thinner until they become a part of the force field of the solid portion of the gel, that is, they are strongly adsorbed to the solid surfaces surrounding the gel pores. These extremely thin layers of water are difficult to move but are moved, nonetheless, by the action of surface tensile forces acting from an exterior drying surface as well as by forces resulting from external loads or hydrostatic heads. When other things are equal, the rate of water passage through concrete is directly proportional to the driving force or vapor pressure difference between the two faces of the membrane. Vapor pressure difference can be the result entirely of external hydrostatic pressure, or it can be combined with differences in relative humidity between faces, or the humidity differences alone can establish a vapor pressure difference.

RESEARCH PROGRAM

Test Specimens and Permeameters

Disks of concrete 6 inches in diameter were cast in steel molds such as those shown in Figure 1. From left to right the thicknesses of the molds are 1 inch, 2 inches, and 4 inches. The 1-inch-thick mold had one piece of 2 x 2-inch, no. 14 galvanized steel mesh placed at middepth. The 2-inch-thick mold had one piece of 2 x 2-inch, no. 12 galvanized steel mesh placed at middepth, and the 4-inch-thick mold had two pieces of the same mesh as for the 2-inch-thick mold placed at one-third and two-thirds depths. The specimens were finished lightly with a steel trowel.

The concrete specimens were encased in an acrylic falling head type permeameter similar to those used by Lorman.[11] The component parts of the permeameter are shown in Figure 2. Acrylic cement was used to attach adjacent acrylic parts, and a casting resin was used to seal the concrete disk in its proper position. Some of the completed permeameters can be seen in Figure 3. In the permeameters standing on legs, the lower or downstream face of the concrete specimen is open to the ambient humidity and temperature. In the permeameters with the enclosed bottoms, the standing water assures that the lower face of the concrete is exposed to 100% RH. A small hole in the lower enclosed case precludes pressure buildup. The upper or upstream face of each specimen was continually exposed to water. At the beginning of each test cycle, the standpipes, shown in Figure 3, were filled with distilled water to a level about 18 inches above the top of the permeameter. The standpipes were about 24 inches high to assure no loss of water by evaporation from the top (minimum length of 10 diameters above the water surface).

Test Procedure

After 14 days of fog curing (100% RH and 73°F), the concrete disks were encased in the permeameters. Some specimens were placed in permeameters with enclosed bottoms, exposing the lower face of the concrete continually to 100% RH. Others were placed in permeameters with open bottoms; thus the lower face of the concrete was exposed to a drying ambient humidity and temperature. Originally, the environments used for lower face exposure were 25% RH, 70% RH, and 100% RH, with the temperature at 73°F in all cases. Part way through the study, the 70% RH environment was changed to 50% RH. After several cycles of exposure to one environment, some of the specimens were moved to different environments.

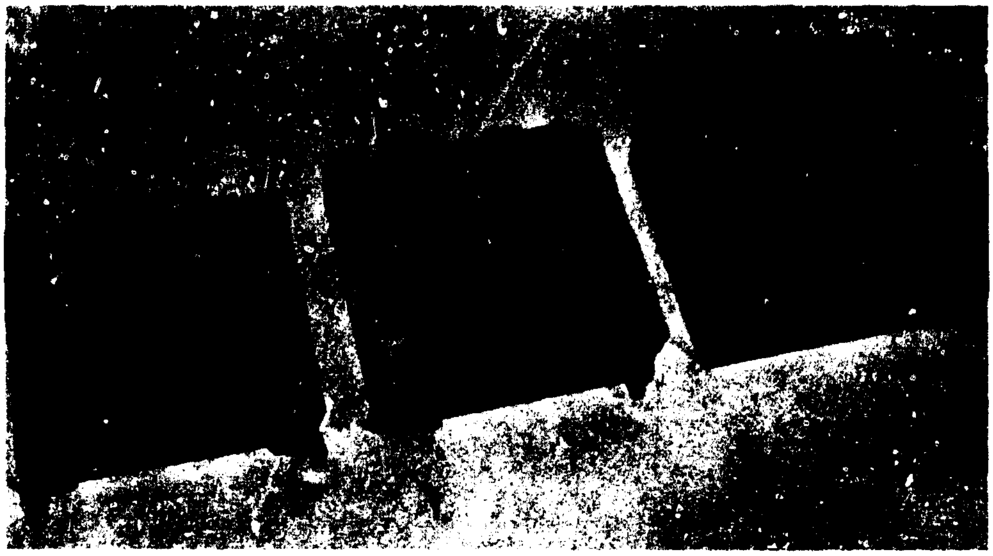


Figure 1. Steel molds for permeability specimens.

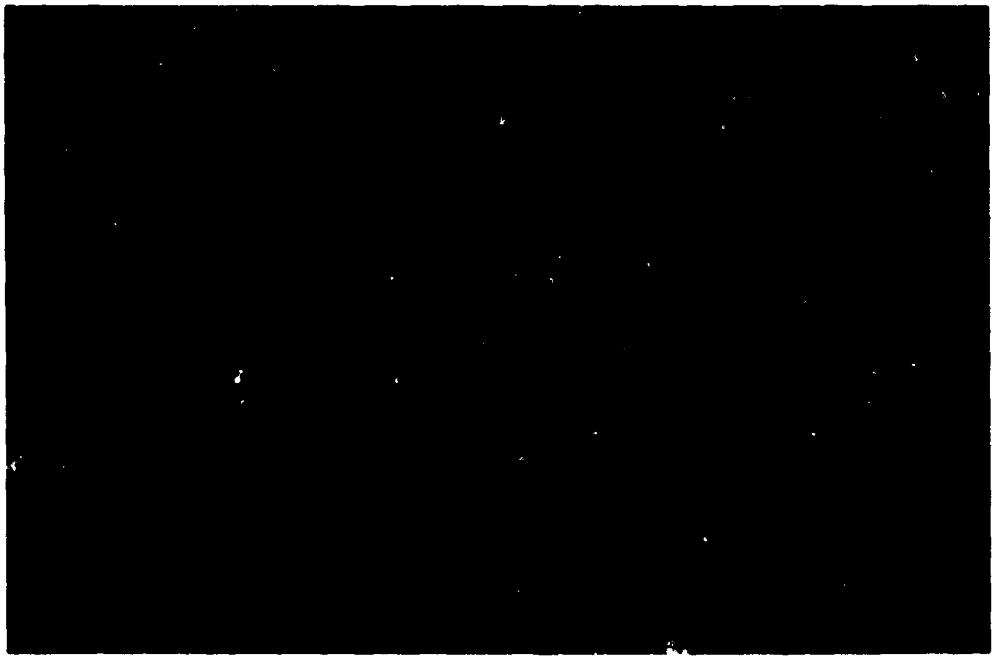


Figure 2. Falling-head permeameters.

Figure 3. Specimens undergoing tests in permeameters.

The standpipes were filled with distilled water to a level about 18 inches above the top of the permeameter, making a total original head over the concrete disk of about 20 inches. To facilitate data recording, all measurements were made from the top of the permeameter and are so presented in this report. To obtain true water level over the concrete specimen, 1-7/8 inches should be added to all heads reported herein. The head of water was allowed to fall in accordance with the degree of permeability of the concrete and the influence of the lower face exposure conditions. Readings of the falling head were made two or three times a week until the head was between 1 and 2 inches above the top of the permeameter, at which time the standpipe was refilled to about 18 inches above the top of the permeameter and the cycle repeated. A "cycle" as used in this report is arbitrarily defined as the time in days required for the water level in the standpipe to drop from a head of 16 inches to a head of 4 inches.

Phase 1, Normal-Weight Concretes

Falling-head readings were made on specimens (disks) of two different normal-weight concretes fabricated in accordance with ACI Standard 525-63.[12] One concrete, with a nominal 28-day compressive strength of 5,000 psi and designated in this report as 8.25NW (8.25 sacks of cement/yd^3, normal weight), was made with a nominal maximum size of aggregate of 3/8 inch, the maximum water content was 5 gallons per sack of cement, and the slump was 3 inches. A limited number of tests were made with a second normal-weight concrete having a nominal compressive strength of 4,000 psi and designated herein as 6.5NW (6.5 sacks of cement/yd^3, normal weight). It was also made with a nominal maximum size of aggregate of 3/8 inch and had a maximum water content of 6.5 gallons per sack of cement, and a slump of 3 inches. For both normal-weight concretes, the cement used was portland type III. The particulars of both normal-weight mixes are shown in Appendix A.

Phase 2, Lightweight Concretes

Permeability factors were determined on two lightweight concretes. One concrete was a sand—lightweight concrete with 3/8-inch expanded shale as coarse aggregate and normal-weight river sand as fine aggregate. This mix is designated in this report as 6.5SLW (6.5 sacks of cement/yd^3, sand—lightweight). The design compressive strength was 5,000 psi at 14 days, the slump was 3 inches, the entrained air content ranged between 5% and 6%, and the cement was portland type III. The wet unit weight averaged about 112 lb/ft^3.

The second lightweight concrete, designated herein as 7LW (7 sacks of cement/yd^3, lightweight), utilized 3/8-inch expanded shale as coarse aggregate but also had expanded shale sand as the fine aggregate. The design compressive strength was 5,000 psi in 14 days, the slump was 3 inches, the entrained air content was 5% to 6%, and the cement used was portland type III. The wet unit weight averaged about 99 lb/ft^3. Particulars of both lightweight concretes are shown in Appendix A.

Phase 3, Miscellaneous Tests

After reaching fairly constant values for permeability in a given environment, selected specimens were treated with boiled linseed oil and again subjected to falling heads in the same environment. In addition, at the close of the study several of the specimens were broken and the amount of corrosion of the galvanized mesh was determined.

On a very limited scale, permeability tests were made on concretes containing (1) an expansive cement and (2) type II portland cement rather than type III. Results of these tests are presented in Appendix B. Due to the limited number of tests, no significant conclusions can be made.

EXPERIMENTAL RESULTS

Phase 1, 8.25NW and 6.5NW Concretes

8.25NW Concrete. The experimental program for 8.25NW concrete is shown in Table 1, and test results are presented in Table 2 for specimens 1 inch thick. Since all three specimens came from the same batch of concrete and were all treated alike, there is no way to explain the differing results shown for specimen 466B. On the basis of the data shown, water passes through specimen 466B twice as fast as through the other two. There were no visible cracks in specimen 466B. In addition, there was no evidence of wetness on the lower face of any of the specimens; this means that water came out of the concrete in vapor form.

As a general rule, the number of days per cycle increases with each succeeding cycle at the same exposure. This can also be seen in Figure 4, in which days per cycle are plotted versus the total time that the upper face had been under water. After several cycles at 25% RH, two of the specimens were subjected to a second exposure of 50% RH. The results of tests after reexposure are also shown in Table 2. Since the vapor pressure difference is not as great between 50% RH and 100% RH as it is between 25% RH and 100% RH, the "driving force" to move water through the concrete is less. The water should move more slowly through the concrete when the lower face is exposed to 50% RH than when exposed to 25% RH. Data in Table 2 confirm this. Plots typical of observed head readings on all permeameters in this study are shown in Figure 5.

The two specimens (467B and 464B) were later returned to their original exposure of 25% RH (Table 2). It was no surprise to find that the time required for one cycle dropped considerably from what it had been at 50% RH but did not drop as low as it had been at 25% RH for the first exposure. This is due, at least in part, to the incremental cement hydration which took place while the specimen was exposed to 50% RH. The effects of the three exposures can also be observed in Figure 4. It might be possible to line up the 25% RH curves for specimen 467B as if the exposure in 50% RH had no effect other than time; however, there is insufficient data to verify this. Coincidence of the curves is unlikely because the concrete, being highly hygroscopic and continually changing in microstructure, would not have the same matrix after exposure to 50% RH that it would have if it had been continually at 25% RH.

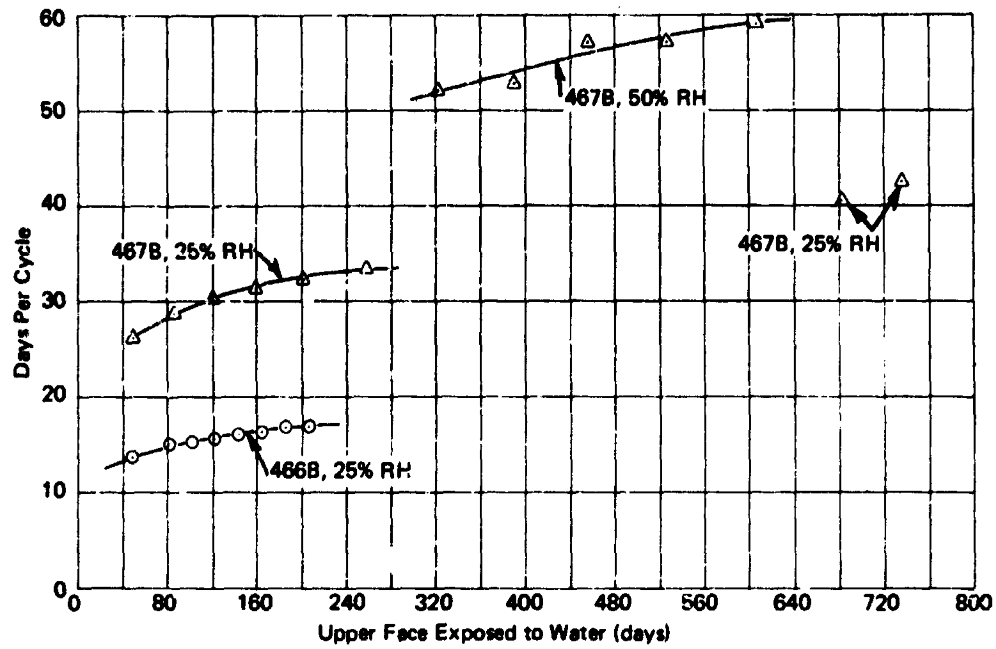


Figure 4. Days per cycle for various humidities, 8.25NW concrete, specimens 1 inch thick.

Table 2 also shows data for a specimen exposed only to 50% RH. As before, the number of days per cycle increases with each succeeding cycle. Theoretically, it should have taken longer for one cycle at 50% RH than at 25% RH; however, data in Table 2 seem better related to data for specimen 466B (Table 2) than to the data for the other specimens.

Table 2 shows days per cycle for specimens first exposed to 70% RH. As noted previously the results for two of the specimens (473B and 468B) agree, while specimen 464B shows about half the number of days per cycle. As expected, subsequent exposures to drier environments revealed less time required per cycle.

Results from specimens with their lower faces exposed to 100% RH are also presented in Table 2. Since the upper face is exposed to water and the lower face to 100% RH, there is no driving force resulting from a vapor pressure difference. The only motive force is the head of water, which is decreasing as water passes into and through the concrete. For this reason alone, the time required to complete a cycle should be somewhat greater than for those specimens subjected to a drying environment on the lower face.

Table 1. Experimental Program For 8.25NW Concrete

Specimen Thickness (in.)	First Lower Face Exposure		Second Lower Face Exposure		Third Lower Face Exposure	
	Relative Humidity (%)	Cycles[a]	Relative Humidity (%)	Cycles	Relative Humidity (%)	Cycles
1	25	8	50	5	25	2
1	25	6	50	7	25	2
1	25	5	70	1	50	1
2	25	6	50	6	25	6
2	25	4	–	–	–	–
2	25	5	50	5	25	1
4	25	8	50	1	–	–
4	25	3	50	5	25	1
4	25	7	–	–	–	–
1	50	6	–	–	–	–
2	50	5	–	–	–	–
4	50	3	–	–	–	–
1	70	7	50	9	25	8
1	70	4	25	6	50	3
1	70	5	50	6	25	2
2	70	6	25	9	50	5
2	70	4	50	5	25	2
2	70	4	25	7	50	3
4	70	4	25	6	50	3
4	70	4	–	–	–	–
4	70	3	50	5	25	3
1	100	1	50	10	25	8[b]
1	100	4	–	–	–	–
1	100	1	25	9	50	7
2	100	1	25	7	50	6
2	100	1	50	8	25	8
2	100	4	–	–	–	–
4	100	1	50	5	25	6
4	100	1	50	7	–	–
4	100	1	25	6	50	2
4	100	4	–	–	–	–

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] Subsequently treated with boiled linseed oil.

Table 2. Days Per Cycle[a] for 8.25NW Concrete, Specimens 1 Inch T

(Exposures at various humidities are sequentially grouped for each spe

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.-													
		1	2	3	4	5	6	7	8	9	10	11	12	13	1
467B	25	26.25	28.25	30.25	31.25	32.25	33.50								
	50							52.00	52.75	57.25	57.25	59.25			
	25												40.25	42.50	
474B	25	21.75	25.75	28.50	29.75	31.50									
	50						42.00	45.00	48.00	50.00	54.00				
	25											37.00	40.50		
466B	25	13.75	15.00	15.25	15.50	16.00	16.25	17.25	17.25						
850C	50	15.50	22.00	27.75	30.25	30.25	32.25								
464B	70	15.75	17.00	18.25	20.50	21.25	24.50	25.50							
	50								20.00	23.25	24.75	24.75	24.75	25.50	25.5
	25														
473B	70	27.00	31.50	37.00	44.75	47.00									
	50						45.75	45.25	48.50	52.25	49.75	52.00			
	25												37.25	40.00	
468B	70	34.50	38.00	43.25	50.75										
	25					35.00	35.50	37.75	38.50	40.00	39.5				
	50											58.50	65.25	70.75	
465B	100	200.00													
	50		11.50	12.00	13.00	13.00	13.50	13.50	14.25	14.25	13.25	15.00			
	25												12.00	13.00	14.2
	25	121.75[b]													
480B	100	156.25													
	25		12.00	13.00	13.50	13.50	14.25	15.50	15.50	15.25	15.25				
	50											20.75	21.25	21.25	22.2
479B	100	131.00	157.75	97.50	94.75										

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

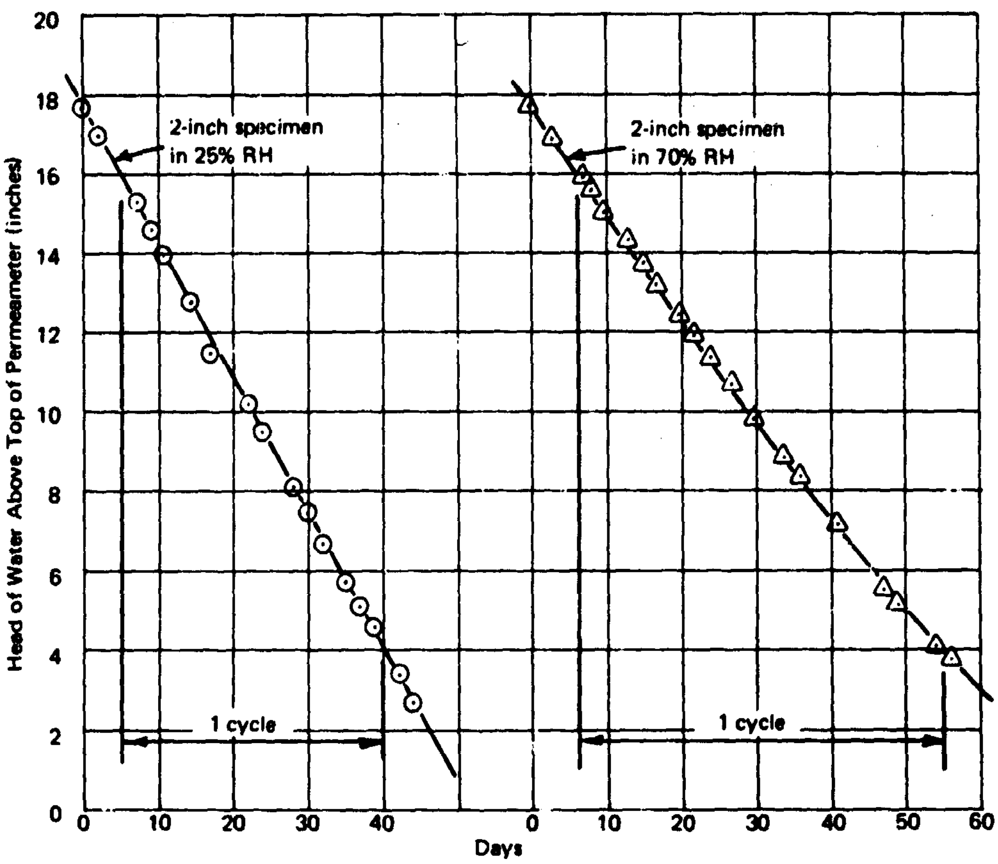
[b] Treated with linseed oil after 19th cycle.

A

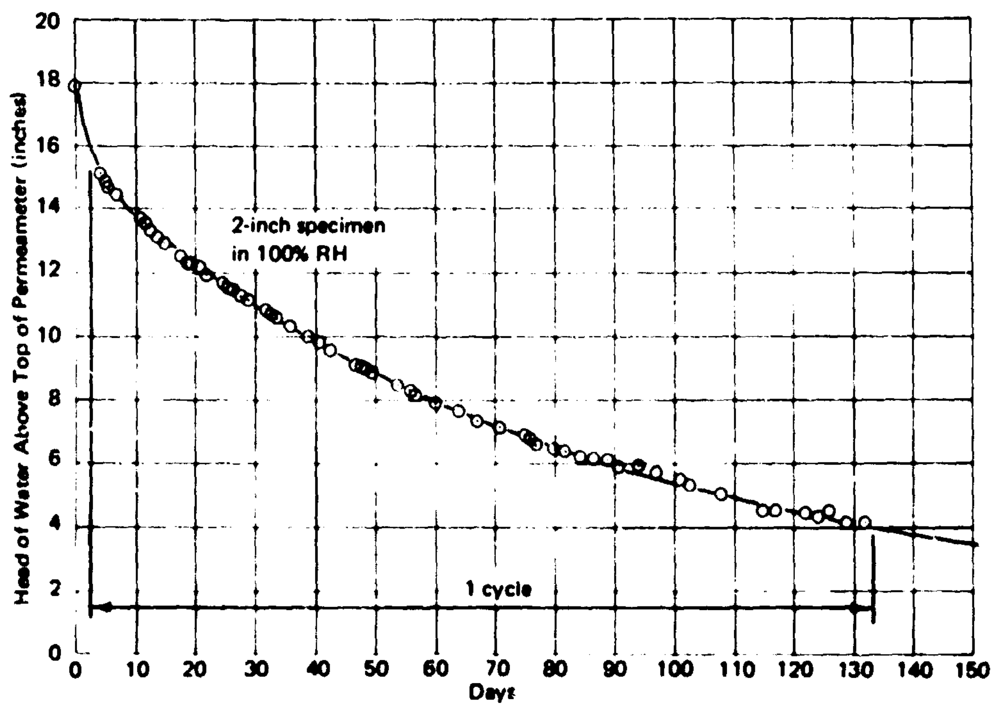
e[a] for 8.25NW Concrete, Specimens 1 Inch Thick

nidities are sequentially grouped for each specimen.)

Days to Complete Cycle No.—																
	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
5	57.25	57.25	59.25	40.25	42.50											
0	50.00	54.00	37.00	40.50												
5																
0	23.25	24.75	24.75	24.75	25.50	25.50	27.00	26.00	16.25	19.00	19.75	19.50	20.25	22.25	23.25	22.25
0	52.25	49.75	52.00	37.25	40.00											
0	40.00	39.50	58.50	65.25	70.75											
5	14.25	13.25	15.00	12.00	13.00	14.25	14.00	14.25	14.25	15.00	15.25					
0	15.25	15.25	20.75	21.25	21.25	22.25	23.25	22.75	23.75							



(a) Plots for specimens in 25% RH and 70% RH.



(b) Plot for specimen in 100% RH.

Figure 5. Typical plots for falling-head permeameter data.

Another factor contributing to greater resistance to water passage in 100% relative humidity is that cement hydration continues at a relatively high rate throughout the entire specimen; thus, hydration products are continually blocking passages. There is fairly good agreement among the three specimens through the second cycle for specimen 479B. The third and fourth cycles, however, show drastic changes, which are unexplainable as far as physical appearances are concerned. That is, there were no visible cracks or other detectable sources of leaks. Furthermore, the consecutive head readings showed the same curvilinear relationship to each other as they did during the other cycles. Most likely these results reflect the ever-changing complex nature of the matrix of concrete. Perhaps in these specimens the development of hydration products caused blockage of some water paths only to open other paths.

After one cycle at 100% RH, the bottom enclosure was removed from specimen 465B and from specimen 480B, and the lower face in each case was exposed to drying. When subjected to 100% RH, specimen 465B was somewhat more resistant to water passage than was specimen 480B, yet when the first is exposed to 50% RH and the second to 25% RH, the data are about the same. Strangely, specimen 465B, when subjected to a third exposure in 25% RH, behaved about the same as it had at 50% RH. Specimen 480B, on the other hand, when placed in a third exposure of 50% RH, showed the expected slower rate of passage for the higher humidity. The treatment of specimen 465B with linseed oil is discussed in a later section of this report.

Results of tests on specimens 2 inches thick first exposed to 25% RH are presented in Table 3. As observed with the 1-inch specimens, data for two of the specimens agree, while the third is somewhat different. As the exposure humidity increased, the time required per cycle increased, as expected; and when the exposure humidity was decreased the cycle time also decreased.

Data are also presented in Table 3 for a specimen (no. 851C) exposed only to 50% RH. Quantitatively, the results seem to jibe better with the results for specimen 463B for the first exposure of 25% RH and agree quite well with data during the third exposure of that specimen (50% RH).

Data for first exposure at 70% RH for specimen 461B are somewhat different from those for the other two, but these data do have a reasonable relationship with those for specimen 463B. Results for specimen 475B and specimen 469B agree fairly well and, generally, have the expected relationship with data shown for specimens 476B and 470B. That is, water passage should take longer in specimens exposed to a higher humidity at the lower face. Results for second and third exposures to 70% RH (Table 3) are similar to the previous ones

Table 3. Days Per Cycle[a] for 8.25NW Concrete, Specimens 2 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—												
		1	2	3	4	5	6	7	8	9	10	11	12	13
463B	25	21.50	21.75	21.75	22.50	23.00	23.75							
	70							37.00						
	50								32.00	33.50	34.50	35.50	35.25	36.00
476B	25	34.00	36.25	38.25	39.00	39.25						47.00		
	50						51.00	59.25	63.75	64.00	64.75			
470B	25	32.25	33.75	35.25	35.50									
851C	50	20.00	28.50	34.25	33.75	37.75								
461B	70	19.75	21.25	22.00	24.75	27.75	28.75							
	25							21.00	22.00	23.75	23.25	26.00	25.00	23.50
	50													
475B	70	29.00	33.25	38.50	44.50									
	25					34.25	33.25	35.25	37.25	36.50	38.00	34.50		
	50												50.00	55.00
469B	70	38.00	42.75	49.25	56.50									
	50					52.75	53.25	56.00	57.75	59.75				
	25										45.00	45.25		
462B	100	211.00												
	25		16.00	17.00	17.75	17.75	20.25	20.50	20.25					
	50									26.50	26.50	27.50	28.50	28.50
481B	100	132.75												
	50		18.00	17.50	18.25	18.50	19.00	19.50	19.75	19.50				
	25										16.25	17.00	17.75	17.25
482B	100	70.00	204.75	108.50	117.75									

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

ᵖer Cycle[a] for 8.25NW Concrete, Specimens 2 Inches Thick

ious humidities are sequentially grouped for each specimen.)

	Days to Complete Cycle No.—														
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	23.75	37.00	32.00	33.50	34.50	35.50	35.25	36.00	27.50	26.25	25.75	29.00	28.25	30.00	
5	51.00	59.25	63.75	64.00	64.75	47.00									
5															
5	28.75	21.00	22.00	23.75	23.25	26.00	25.00	23.50	24.50	24.50	33.75	34.25	33.25	35.00	35.50
5	33.25	35.25	37.25	36.50	38.00	34.50	50.00	55.00	58.25						
5	53.25	56.00	57.75	59.75	45.00	45.25									
5	20.25	20.50	20.25	26.50	26.50	27.50	28.50	28.50	29.25						
0	19.00	19.50	19.75	19.50	16.25	17.00	17.75	17.25	18.50	20.00	21.50	22.50			

ches to 4 inches.

B

Data in Table 3 for first exposure in 100% RH show the cycle times are much longer than in the drier exposures. The reasons for the decrease in cycle time noted in specimen 482B after cycle 2 are unexplainable, as was a similar decrease for specimen 479B (Table 2). Results due to subsequent exposures at drier humidities were quite similar to those seen in Table 2 for the 1-inch specimens first exposed to 100% RH.

Days per cycle for specimens 4 inches thick are shown in Table 4. The results for specimens 472B and 477B first exposed to 25% RH and then to 50% RH show longer cycle times as expected. Cycle times for specimen 852C exposed only to 50% RH appear to reflect the expected trend. Although results in Table 4 for the three specimens first exposed to 70% RH show quite close agreement with each other, they do not seem compatible with cycle times for 4-inch specimens in 25% and 50% RH. Subsequent exposures for specimen 483B show shorter cycle times at 25% RH and then longer again at 50% RH, as expected. Specimen 510B, however, when initially exposed to 50% RH showed only a slight drop in days per cycle, followed by a rapid increase to cycle times exceeding those at 70% RH. A third exposure, at 25% RH, reduced the days per cycle as expected.

In the case of the 4-inch-thick specimens first exposed to 100% RH (Table 4), as expected, cycle times were considerably longer than for the drier humidities. It is interesting that specimen 509B showed a reduction in days per cycle after the second cycle, as had one of the 2-inch-thick specimens (no. 481B, Table 3) and one of the 1-inch-thick specimens (no. 465B, Table 2). Subsequent drier exposures of the 4-inch-thick specimens showed expected shorter cycle times.

Table 5 summarizes results of falling-head permeameter tests on 8.25NW concrete. The cycle times were averaged when multiple specimens were used. Reading horizontally, the thicker specimens show consistently longer cycle times in 25% RH, 50% RH, and 70% RH, but the trend is somewhat disrupted in the 100% RH tests, in which only one specimen was used for each thickness. Reading vertically, the cycle times become consistently longer as the exposure humidity increases except for 4-inch-thick specimens in 70% RH.

6.5 NW Concrete. The experimental program for 6.5NW concrete is shown in Table 6. Results for 1-inch-thick specimens exposed to 25% RH and to 50% RH are presented in Table 7. The data have the familiar relationship of longer cycle time required for more humid exposure. Days per cycle for 2-inch-thick specimens exposed to 25% RH, 50% RH, and 100% RH are shown in Table 8. The results for all the 2-inch-thick specimens are reasonably consistent.

Table 4. Days Per Cycle[a] for 8.25NW Concrete, Specimens 4 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—												
		1	2	3	4	5	6	7	8	9	10	11	12	13
472B	25	58.75	55.75	56.75	59.25	63.00	60.50	60.50	63.25					
	50									75.00				
477B	25	43.75	52.00	51.75										
	50				61.50	66.00	69.75	74.50	75.25					
	25									57.00				
852C	50	36.00	50.75	56.75										
483B	70	26.75	34.25	37.25	41.75									
	25					37.00	34.75	35.25	36.50	35.75	36.75			
	50											42.75	52.75	57.00
510B	70	35.75	41.25	47.00										
	50				46.25	47.75	50.00	52.00	54.00					
	25									41.50	39.00	41.00	43.25	
484B	70	28.00	34.25	37.50	43.25									
471B	100	176.25												
	50		48.50	46.50	47.75	46.00	50.00	50.50	52.25					
508B	100	107.75												
	25		36.50	33.00	34.25	34.25	37.25	37.00						
	50								48.00	56.25				
509B	100	97.75	191.00	110.25	110.25									

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table 5. Summary of Test Results for 8.25NW Concrete

Relative Humidity of First Exposure (%)	Average[a] Days Per Cycle and Number of Cycles for Specimens—					
	1 Inch Thick		2 Inches Thick		4 Inches Thick	
	Days	Cycles[b]	Days	Cycles	Days	Cycles
25	24.75	3	31.75	3	54.25	3
50	27.75[c]	3	34.25[c]	3	58.75[c]	3
70	32.75	3	36.50	3	40.50	3
100	167.75[c]	2	204.75[c]	2	191.00[c]	2

[a] Averages rounded off to the nearest 0.25 day.

[b] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[c] One test specimen only.

Table 6. Experimental Program For 6.5NW Concrete

Specimen Thickness (in.)	First Lower Face Exposure		Second Lower Face Exposure	
	Relative Humidity (%)	Cycles	Relative Humidity (%)	Cycles
1	25	5	–	–
2	25	12	–	–
2	25	12	50	5
4	25	8	–	–
1	50	4	–	–
1	50	4	–	–
2	50	4	–	–
2	100	2	–	–

Table 7. Days Per Cycle[a] for 6.5NW Concrete, Specimens 1 Inch Thick

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—				
		1	2	3	4	5
933C	25	18.75	22.50	25.00	25.75	27.25
934C	50	20.75	28.75	34.00	36.00	
935C	50	26.75	36.75	42.50	45.75	

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table 8. Days Per Cycle[a] for 6.5NW Concrete, Specimens 2 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
860B	25	16.00	17.75	17.50	17.75	18.25	20.00	20.00	20.00	19.00	22.25	20.50	19.50					
	50													29.00	30.00	29.00	31.00	31.00
859B	25	14.75	17.00	14.00	16.00	16.25	12.50	18.00	17.75	18.25	21.00	22.50	22.00					
936C	50	27.50	32.25	35.00	38.25													
861B	100	83.00	309.50															

[a] One cycle is the time in days required for the water head to fall from 16 inches to 4 inches.

Results of a test on a specimen 4 inches thick are presented in Table 9. This specimen was cured for 14 days in fog (as were all the specimens), and then it was allowed to dry at 25% RH for 294 days prior to being encased in the permeameter. The lower face was then exposed to 25% RH. In the first few cycles, the water passed into the concrete very quickly because the upper portion of the specimen was dry. After the fifth cycle, the days per cycle approached and then later exceeded typical values for other specimens at 25% RH. If the 4-inch-thick specimen had reached a state of moisture equilibrium with the 25% RH environment in the 294 days, the high adsorptive forces in the specimen would cause the center of the specimen to be at a relative humidity somewhat higher than 25%. In the presence of this somewhat higher humidity, hydration of cement would have been fairly complete by the end of the 294 days. After encasement in the permeameter and exposure to water on the upper face, the humidity level would rise rather rapidly and hydration of the remaining unhydrated cement would resume. The gradually increasing volume of hydration products would then tend to slow down the passage of water.

Comparisons of 8.25NW and 6.5NW Concretes. Table 10 compares 8.25NW and 6.5NW concretes. The concrete mixes differ principally in W/C and in cement content. The results shown in Table 10 for 25% RH are rather confusing. The 1-inch-thick specimens reveal little difference between the two concretes, but cycle times for the 2-inch-thick 8.25NW specimens are almost twice as long as for the 6.5NW specimens of the same thickness. This relationship is reversed, however, in the results shown for the rest of the specimens of both thicknesses in 50% RH and 100% RH. The trend for these tests seems to be that the 6.5NW concrete was slightly less permeable than the 8.25NW concrete. Because (1) it is generally accepted that concrete with a lower W/C and higher cement content is less permeable, and (2) multiple specimens were lacking in places, it may be more realistic to state that there seems to be little difference in permeability between the two concretes.

Phase 2, 6.5SLW and 7LW Concretes

6.5SLW Concrete. The experimental program for 6.5SLW concrete is shown in Table 11. The results for specimens 1 inch thick are presented in Table 12. As noted before in several instances, results for two of the specimens first exposed to 25% RH agree, while results for the other one are significantly different. The expected effects of longer cycle times in wetter and then shorter cycle times in drier environments were demonstrated in subsequent exposures. Results of treating one of the specimens with boiled linseed oil are discussed in a later section of this report.

Table 9. Days Per Cycle[a] for 6.5NW Concrete, Specimen 4 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—							
		1	2	3	4	5	6	7	8
863B[b]	25	1.00	2.00	2.75	6.75	16.50	31.00	44.50	55.00

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] The specimen was cured in fog for 14 days and then allowed to dry at 25% RH for 294 days prior to being encased in permeameter.

Table 10. Comparison of 8.25NW and 6.5NW Concretes

Relative Humidity of First Exposure (%)	Specimen Thickness (in.)	Average[a] Days Per Cycle and Number of Cycles for Concretes—			
		8.25NW (W/C = 0.44)[b]		6.5NW (W/C = 0.55)[c]	
		Days	Cycles	Days	Cycles
25	1	25.50	4	25.75[d]	4
25	2	32.25	4	17.00	4
50	1	30.25[d]	4	41.00	4
50	2	33.75[d]	4	38.25[d]	4
100	2	204.75[d]	2	309.50[d]	2

[a] Averages rounded off to nearest 0.25 day.

[b] W/C of 0.44 is equivalent to about 5 gallons of water per sack of cement.

[c] W/C of 0.55 is equivalent to about 6.2 gallons of water per sack of cement.

[d] One specimen only.

Table 11. Experimental Program for 6.5SLW Concrete

Specimen Thickness (in.)	First Lower Face Exposure		Second Lower Face Exposure		Third Lower Face Exposure	
	Relative Humidity (%)	Cycles[a]	Relative Humidity (%)	Cycles	Relative Humidity (%)	Cycles
1	25	6	50	8	25	10
1	25	5	50	7	25	4[b]
1	25	10	50	4	–	–
2	25	13	50	7	–	–
2	25	9	50	4	–	–
2	25	12	50	5	–	–
4	25	8	50	2	–	–
4	25	8	50	2	–	–
4	25	7	–	–	–	–
1	50	7	–	–	–	–
1	50	3	–	–	–	–
1	50	2	–	–	–	–
2	50	7	25	6	–	–
2	50	10	–	–	–	–
2	50	5	–	–	–	–
4	50	5	25	3	–	–
4	50	1	–	–	–	–
4	50	2	–	–	–	–
1	70	3	50	11	25	10[b]
1	70	1	50	14	25	10
1	70	1	50	10	25	7
2	70	2	50	9	25	5
2	70	–	50	2	–	–
4	70	2	50	7	25	5
4	70	1	50	5	25	2
1	100	2	25	3	–	–
1	100	2	50	2	–	–
1	100	3	–	–	–	–
2	100	10	–	–	–	–
2	100	4	–	–	–	–
2	100	2	–	–	–	–
4	100	2	50	5	25	2
4	100	3	50	2	–	–
4	100	3	25	2	–	–

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] Subsequently treated with boiled linseed oil and then exposed to 25% RH

Results of first exposures of 1-inch-thick specimens in 50% RH, 70% RH, and 100% RH are also listed in Table 12 Cycle times for first exposure to 25% RH, 50% RH, and 70% RH do not vary much. Results in subsequent exposures seem to reflect the expected effects of exposure to wetter and drier humidities.

Days per cycle for specimens 2 inches thick are shown in Table 13. Results in 25% RH and 50% RH seem to have the proper relationship, but the specimen in 70% RH seems to show little change from the 25% RH results. As noted in other tests, the longest days per cycle are registered by specimen (798B) first exposed to 100% RH.

Table 14 shows results for specimens 4 inches thick. With the exception of specimen 849C, there is not much difference between exposures in 25% RH and 50% RH. Number of days per cycle for the specimen in 70% RH tend to be fewer than those for specimens in either 25% RH or 50% RH, rather than greater as expected for a wetter exposure.

The results of tests on 6.5SLW concrete are summarized in Table 15. The 4-inch-thick specimens show longest cycle times for the 25% RH, 50% RH, and 70% RH exposures. Results in 100% RH vary considerably with respect to the effects of thickness.

7LW Concrete. The experimental program for 7LW concrete is outlined in Table 16. Test results for specimens 1 inch thick are shown in Table 17. Generally, the trend is the wetter the exposure, the longer the cycle times. Two exceptions are noted—specimens 984B and 991C. Cycle times for specimens 2 inches thick are reported in Table 18. As with the 1-inch specimens, the trend is longer cycle times in wetter exposures. Results of tests on specimens 4 inches thick are presented in Table 19. Lower face exposure humidity seems to have relatively little effect of the days per cycle for 4-inch-thick specimens.

The effects of thickness and exposure on the water passage in 7LW concrete are shown in Table 20. The cycle times increase directly with the specimen thickness in 25% RH and 50% RH, but the distinction is not so evident in 100% RH. Compared with the others, the rather lengthy cycle times for 1-inch-thick specimens in 100% RH are difficult to explain. Perhaps the thicker specimens would have shown about the same cycle times as the 1-inch-thick specimens, had more cycles been run. Cycle times increase with wetter exposure for 1-inch-thick and 2-inch-thick specimens, but variations are seen for the 4-inch-thick specimens (for which there was only one specimen each).

Table 12. Days Per Cycle[a] for 6.5SLW Concrete, Specimens 1 In

(Exposures at various humidities are sequentially grouped for each

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
802B	25	14.50	18.75	20.00	22.00	24.00	25.75	25.00	24.75	27.00	26.00						
	50											39.00	39.00	41.50	42.50		
737B	25	10.75	11.50	12.25	12.75	12.50	12.75										
	50							17.50	19.75	20.00	21.00	22.00	22.75	22.75	22.25		
	25															16.50	1
	25																
845B	25	9.75	13.25	14.25	14.50	15.00											
	50						21.50	23.25	24.75	25.50	27.50	26.75	26.75				
	25													19.00	18.50	18.50	1
847C	50	7.00	8.25	10.50	12.75	14.00	15.75	16.00									
736B	70	10.25	13.75	18.50													
	50				15.00	16.75	17.50	17.00	18.25	19.00	19.50	20.75	21.25	21.75	21.50		
	25															16.00	1
843B	70	11.25															
	50		15.50	17.50	18.25	15.50	16.25	14.50	12.75	11.25	11.25	11.75	11.50	12.00	11.75	13.00	
	25																1
	25																
844B	70	5.25															
	50		15.00	18.00	20.25	20.50	23.25	23.00	26.25	28.25	28.50	28.50					
	25												21.50	22.25	21.50	23.50	2
801B	100	113.75	195.25														
	50			27.25	30.25												
262C	100	63.00	206.25														
	25			21.25	23.00	25.00											
738B	100	45.50	111.50	194.75													

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] Treated with linseed oil after 24th cycle.

[c] Treated with linseed oil after 25th cycle.

[a] for 6.5SLW Concrete, Specimens 1 Inch Thick

lities are sequentially grouped for each specimen.)

Days to Complete Cycle No.—															
11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
39.00	39.00	41.50	42.50												
22.00	22.75	22.75	22.25	16.50	15.50	15.50	15.25	16.00	17.25	16.50	17.25	19.50	19.00	129.00[b]	
26.75	26.75	19.00	18.50	18.50	18.50										
20.75	21.25	21.75	21.50	16.00	16.00	16.00	15.50	16.25	17.50	16.50	17.50	18.50	18.50		
11.75	11.50	12.00	11.75	13.00	10.75	11.25	9.50	10.75	10.75	11.25	11.00	11.50	11.75	12.00	105.00[c]
28.50	21.50	22.25	21.50	23.50	24.75	26.50	28.25								

B

Table 13. Days Per Cycle[a] for 6.5SLW Concrete, Specimens 2 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
734B	25	16.00	15.50	16.25	16.00	16.75	17.50	18.50	19.50	18.25	17.75	18.00	19.25	18.50		
	50														25.25	29.0
796B	25	26.25	25.50	24.50	26.00	27.50	26.75	26.75	29.25	27.75						
	50										39.25	41.00	43.00	44.50		
848B	25	15.25	18.75	17.75	18.50	19.75	20.75	20.50	20.00	19.50	21.25	20.25	19.25			
	50													29.00	30.50	32.0
263C	50	26.25	24.50	26.00	29.00	31.50	33.00	34.75								
	25								26.75	26.00	27.00	28.50	29.00	30.00		
106C	50	25.25	25.50	28.50	31.50	34.25	36.00	39.75	39.75	42.00	44.25	44.75				
848C	50	16.00	19.25	24.00	31.75	36.25										
733B	70	17.25	20.25													
	50			19.50	20.75	22.25	22.75	23.25	24.50	25.50	27.00	26.50				
	25												20.25	19.25	19.50	18.7
	50															
798B	100	131.00	247.00													

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

A

B

;LW Concrete, Specimens 2 Inches Thick

sequentially grouped for each specimen.)

ıys to Complete Cycle No.—											
9	10	11	12	13	14	15	16	17	18	19	20
18.25	17.75	18.00	19.25	18.50	25.25	29.00	27.75	28.50	28.75	29.50	29.50
27.75	39.25	41.00	43.00	44.50							
19.50	21.25	20.25	19.25	29.00	30.50	32.00	32.25	33.00	32.75		
26.00	27.00	28.50	29.00	30.00							
42.00	44.25	44.75									
25.50	27.00	26.50	20.25	19.25	19.50	18.75	18.25	25.25	30.00		

's.

B

Table 14. Days Per Cycle[a] for 6.5SLW Concrete, Specimens 4 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
794B	25	54.25	42.75	42.00	42.25	41.75	43.25	43.75	42.00						
	50									49.50	59.50				
795B	25	53.75	40.75	38.75	38.50	38.00	40.25	39.00	40.50						
	50									47.25	56.50				
265C	25	60.50	44.00	41.25	42.75	41.50	50.75	60.75	63.25						
264C	50	42.25	45.25	43.75	46.50	49.00									
	25						45.25	41.75	41.50						
53D	50	40.50													
849C	50	37.00	72.75												
718B	70	13.50	37.75												
	50			30.75	31.50	31.50	32.50	34.00	35.25	35.00					
	25										30.00	27.75	27.75	28.75	30.00
719B	100	28.25	109.00												
	50			41.00	31.00	30.50	32.75	33.00							
	25								30.00	29.75					
720B	100	27.50	109.75	223.75											
	50				39.50	26.75									
849B	100	31.75	120.00	178.00											
	25				33.00	27.75									

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table 15. Summary of Test Results for 6.5SLW Concrete

Relative Humidity of First Exposure (%)	Average[a] Days Per Cycle and Number of Cycles for Specimens—					
	1 Inch Thick		2 Inches Thick		4 Inches Thick	
	Days	Cycles[b]	Days	Cycles	Days	Cycles
25	17.25	5	21.25	5	40.50	5
50	14.00[c]	5	34.00	5	49.00[c]	5
100	171.00	2	247.00[c]	2	113.00	2

[a] Averages are rounded off to nearest 0.25 day.

[b] One cycle is the time in days for water head to fall from 16 inches to 4 inches.

[c] One specimen only.

Table 16. Experimental Program For 7LW Concrete

Specimen Thickness (in.)	First Lower Face Exposure		Second Lower Face Exposure	
	Relative Humidity (%)	Cycles[a]	Relative Humidity (%)	Cycles
1	25	6	50	3
1	25	10	–	–
1	25	6	–	–
2	25	6	–	–
2	25	4	–	–
2	25	4	–	–
4	25	2	–	–
1	50	8	–	–
1	50	2	–	–
1	50	7	–	–
1	50	3	–	–
1	50	1	–	–
2	50	4	25	1
2	50	3	25	*b*
2	50	3	25	*b*
2	50	1	–	–
4	50	2	25	*b*
4	50	1	–	–
4	50	*b*	–	–
1	100	2	–	–
1	100	2	–	–
2	100	2	50	*b*
2	100	2		
2	100	2		
4	100	2		

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] Cycle not completed

Table 17. Days Per Cycle[a] for 7LW Concrete, Specimens 1 Inch Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—									
		1	2	3	4	5	6	7	8	9	10
452C	25 50	14.50	22.75	29.00	32.00	37.75	38.50	 60.50	 70.50	 76.50	
415C	25	17.25	22.00	31.25	35.25	36.75	41.25	44.00	46.50	50.00	55.00
985B	50	16.75	22.50	33.75	44.50	57.00	64.75	74.50	85.75		
984B	50	13.50	18.00								
128C	50	23.50	30.00	42.75	60.25	69.50	78.25	87.00			
991C	50	34.50	35.75	26.00							
129C	100	59.00	519.25								
130C	100	55.75	468.00								

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table 18. Days Per Cycle[a] for 7LW Concrete, Specimens 2 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—					
		1	2	3	4	5	6
907B	25	43.00	56.25	7[illegible].75	80.50	87.50	87.50
381C	25	44.00	85.25	90.75	101.25		
416C	25	58.00	89.50	93.75	101.50		
908B	50	39.25	73.50	104.75	126.50		
	25					111.00	
382C	50	31.25	114.50	144.75			
417C	50	52.50	108.25	141.50			
383C	100	38.25	202.00				
	50			[b]			
906B	100	59.00	337.00				
456C	100	54.00	394.75				

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] Water at 13 inches after 60 days.

Table 19. Days Per Cycle[a] for 7LW Concrete, Specimens 4 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—	
		1	2
904B	25	73.25	269.75
905B	50	46.75	224.00
84D	50	40.50	
909B	100	37.75	312.00

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table 20. Summary of Test Results for 7LW Concrete

Relative Humidity of First Exposure (%)	Average[a] Days Per Cycle and Number of Cycles for Specimens—					
	1 Inch Thick		2 Inches Thick		4 Inches Thick	
	Days	Cycles	Days	Cycles	Days	Cycles
25	22.50	2	77.00	2	269.75[b]	2
50	26.50	2	98.75	2	224.00[b]	2
100	493.50	2	328.00	2	312.00[b]	2

[a] Averages rounded off to nearest 0.25 day.

[b] One specimen only.

Comparisons of 6.5SLW and 7LW Concretes. Table 21 presents comparisons of results on the two lightweight concretes. The overwhelming trend for all thicknesses and all exposures is that the 7LW concrete presents substantially more resistance to the passage of water through it. Considering the slight differences in W/C and cement content between the two, these results are difficult to understand. The principal reason for the differences is the continuing influence of the water which was absorbed by the lightweight aggregate. Since both concretes contain coarse lightweight expanded shale, the chief difference in aggregate characteristics is that the 7LW contains lightweight expanded-shale sand, whereas the 6.5SLW contains normal-weight river sand. The lightweight aggregate is highly absorptive (8% as against 2% for normal-weight sand) as well as highly porous; and as the inside of the concrete dries, the water absorbed in the lightweight aggregate can be drawn out of the aggregate fairly easily. As the water enters the matrix (cement paste), it begins to hydrate any remaining unhydrated cement with which it comes into contact. The result is a more dense matrix in the immediate vicinity of the aggregate particles, including the rather small particles making up the sand fraction. In short, the hydration process can become more complete because water is available over a longer length of time. The movement of water from the lightweight aggregate particles begins as soon as the matrix begins to desiccate as water is incorporated during the hydration process. Even in a concrete specimen being cured in a 100% RH environment, water movement into concrete has been manifested in the form of swelling.[5] One of the purposes of water curing is to replace the water incorporated during hydration, making possible a more complete hydration. (Hydration is a time-dependent process.) In lightweight aggregate concrete, the interior of the concrete mass probably begins to draw upon the absorbed water shortly after final set.

Table 21. Comparison of 6.5SLW and 7LW Concretes

Relative Humidity of First Exposure (%)	Specimen Thickness (in.)	Average[a] Days Per Cycle and Number of Cycles for Concretes--			
		6.5SLW (W/C = 0.53)[b]		7LW (W/C = 0.51)[c]	
		Days	Cycles	Days	Cycles
25	1	15.50	3	30.00	3
25	2	19.50	3	85.00	3
25	4	42.50	3	269.75	2[d]
50	1	10.50[d]	3	34.25	3
50	2	26.25	3	130.25	3
50	4	59.00	2	224.00[d]	2
100	1	171.00	2	493.75	2
100	2	247.00[d]	2	391.00	2
100	4	113.00	2	312.00[d]	2

[a] Averages are rounded off to nearest 0.25 day.

[b] W/C of 0.53 is equivalent to 6.0 gallons of water per sack of cement.

[c] W/C of 0.51 is equivalent to 5.9 gallons of water per sack of cement.

[d] One specimen only.

Comparisons of Results for All Concretes. Results for all concretes are compared in Table 22, which lists averages where possible and individual values where single specimens were used. Although direct comparison of concretes is probably not legitimate because of basic mix differences, some interesting observations can be made. Generally speaking, the thicker specimens show increasing resistance to water passage, regardless of exposure humidity, the longer the cycle time. Results for single specimens sometimes deviate from what appears to be a reasonable pattern; considering the variations observed among specimens subjected to the same conditions, this is not surprising. Comparisons from concrete to concrete (Table 22) show considerable variation but, generally speaking, the 8.25NW concrete is less permeable than 6.5NW and 6.5SLW concretes but more permeable than 7LW concrete. Stated another way, the 7LW concrete with all-lightweight aggregate appears to be the most impermeable of all, the high porosity of the coarse and fine aggregate notwithstanding. Possible reasons for this apparent anomalous permeability were discussed in the previous section. The 8.25NW concrete, with a W/C of

0.47 and a cement content of 8.25 sacks/yd^3, should be less permeable than the 7LW concrete with a W/C of 0.51 and a cement content of 7 sacks/yd^3. One of the unknowns involved is the effect of the entrained air on permeability of the 6.5SLW and 7LW concretes. Diametrically opposed opinions are found in the literature regarding the effects of entrained air on permeability.

Table 22. Comparison of Average Cycle Times for All Concretes

Relative Humidity of First Exposure (%)	Average[a] Days Per Cycle and Number of Cycles for Concretes—							
	8.25NW		6.5NW		6.5SLW		7LW	
	Days	Cycles	Days	Cycles	Days	Cycles	Days	Cycles
1-Inch-Thick Specimens								
25	24.75	3	25.00[b]	3	15.50	3	30.00	3
50	27.75[b]	3	38.25	3	10.50	3[b]	34.25	3
100	157.75[b]	2	–	–	171.00	2	493.75	2
2-Inch-Thick Specimens								
25	[illegible].75	3	15.75	3	19.50	3	85.00	3
50	34.25	3	35.00[b]	3	26.25	3	130.25	3
100	204.75	2	309.50[b]	2	247.00[b]	2	391.00	2
4-Inch-Thick Specimens								
25	54.00	2	–	–	42.50	2	269.75[b]	2
50	50.75	2	–	–	59.00	2	224.00[b]	2
100	191.00	2	–	–	113.00	2	312.00[b]	2

[a] Averages are rounded off to nearest 0.25 day.

[b] One specimen only.

Phase 3, Miscellaneous Tests

Specimens Coated With Boiled Linseed Oil. The U. S. Bureau of Reclamation[7]* and the American Concrete Institute[13,14] recommend application of boiled linseed oil as a surface sealant and water repellant

* pp. 440-441.

for protection of the concrete from freezing and thawing, from deicing salts, from sulfates, from light petroleum oils, from fats, and from fatty acids. It was therefore decided to treat a few of the permeability specimens with boiled linseed oil. After reaching fairly constant values for resistance to water passage in a given environment, three selected specimens were treated with boiled linseed oil to determine to what degree it would seal the surface against water. The procedure for application of the linseed oil is outlined below.[7]

1. Water was removed from the upper portion of the permeameter and the upper face of the concrete was allowed to dry for several days in 25% RH.

2. The dry upper face of the specimen was then flooded with a solution consisting of 50% mineral spirits and 50% boiled linseed oil heated to 175^{o}F. The solution was allowed to soak in for 1 hour, after which the surplus was removed. The surface of the concrete was allowed to dry for at least 24 hours.

3. The upper face of the concrete specimen was then flooded with 100% boiled linseed oil heated to 175^{o}F which was allowed to soak in for 1 hour. The surplus linseed oil was removed and the surface was allowed to dry for at least 24 hours.

4. The standpipe was refilled with distilled water and falling-head permeameter readings were resumed as before.

The effects of treating the surfaces with linseed oil can be seen in Table 2 for a specimen (465B) made with 8.25NW concrete and in Table 12 for specimens (737B and 843B) made with 6.5SLW concrete. In all cases there was a dramatic increase in number of days per cycle. The linseed oil seems to present to the water a continuous semi-impermeable membrane. This study does not reveal the effects of continued cycling on the maintenance of the continuity of the linseed oil barrier. Recommendations for the use of boiled linseed oil include application of two coats of standard outside white lead and oil paint over the treated surface to protect the linseed oil from rapid deterioration.[7,13,14] The paint was not applied in this study in order to determine the effects of the boiled linseed oil itself upon water movement.

Corrosion of Galvanized Mesh Reinforcement. At the conclusion of the study, several of the specimens were taken from the permeameters and crushed to recover the galvanized mesh reinforcement. The pieces of mesh reinforcement from each specimen, together with unused identical pieces of mesh, were stripped of zinc using the hydrochloric acid method described in ASTM A-90.[15] The percent oxidation of the zinc coating for each specimen

is shown in Table 23. Results for each specimen of three different concretes are listed in descending percentages of oxidation. On the whole, the highest oxidation values are found in specimens of 7LW concrete, somewhat lower values in 6.5SLW concrete, and the lowest in 8.25NW. Although there are some inherent variations to any generalized explanation of concrete behavior, the author believes that the results found in Table 23 can be related to the pH of the concrete matrix.

In recent years, considerable attention has been given to research on corrosion of steel in concrete. Griffin[16,17] has shown that the pH of freshly mixed concrete is quite high (about 13) and has stated that if the pH of the hardened concrete remains above 12, there will be no destructive corrosion of embedded steel. He has also shown that if the pH is lowered to about 10 by intrusion of salts or by carbonation, the conditions become ideal for steel corrosion. Steel with a zinc coating (galvanized) presents a somewhat different situation. The zinc coating is amphoteric; that is, it is highly susceptible to being oxidized to a zincate by a highly alkaline (high pH) solution or to a zinc salt by a highly acidic (low pH) solution and is moderately susceptible to oxidation at any pH. It is least susceptible at a pH of about 9. In this study, other things being equal, the pH of the specimens could be lowered from the original value of about 13 only by dilution with the distilled water used for the tests. The more water which passed through, therefore, the lower the pH might be. In other words, the less the resistance to water passage or the higher the permeability, the lower the pH; the lower the pH, the slower the rate of oxidation of the zinc coating. Conversely, the less the permeability, the higher the pH and the higher the rate of zinc oxidation.

Considering the results shown in Table 22, which indicate that 7LW concrete is least permeable, it is quite reasonable that 7LW concrete should show the highest values for zinc oxidation. Another facet of the water absorption by the lightweight aggregate (discussed previously) is that this water was highly alkaline, so that when, under drying conditions, this water is drawn back into the matrix, it tends to maintain a high pH. It is probably this absorbed highly alkaline water which accounts for the high zinc oxidation rate seen for 6.5SLW concrete, a concrete which shows a relatively high permeability (see Table 22).

Zinc oxidation rates shown in Table 23 for 8.25NW concrete may be typical for a normal-weight concrete at a W/C of 0.47 and a cement content of 8.25 sacks/yd^3. Generally, the lower oxidation rates apply to the specimens which had relatively high permeability. With the exception of the last specimen in Table 23, the 1-inch-thick specimens showed the lowest oxidation rate in Table 23; this means that the pH values in these specimens were probably lowest.

Table 23. Oxidation of Zinc Coating From Mesh Reinforcement

Specimen No.	Specimen Thickness (in.)	First Exposure—		Second Exposure—		Third Exposure—		Total Exposure (days)	Oxidation of Zinc Coating (%)
		% RH	Cycles[a]	% RH	Cycles	% RH	Cycles		
8.25NW Concrete									
482B	2	100	4	–	–	–	--	592	25
472B	4	25	8	50	1	–	–	704	22
483B	4	70	4	25	6	50	3	659	17
464B	1	70	7	50	9	25	8	727	15
461B	2	70	6	25	9	50	5	727	14
479B	1	100	4	–	–	–	–	571	11
463B	2	25	6	50	6	25	6	720	11
6.5SLW Concrete									
106C	2	50	11	–	--	–	–	495	30
264C	4	50	5	25	3	–	–	461	28
846B	2	100	4	–	–	–	–	440	27
720B	4	100	3	50	2	–	–	546	26
734B	2	25	13	50	7	–	–	552	21
798B	2	100	2	–	–	–	–	535	21
733B	2	70	2	50	9	25	5[b]	552	16
738B	1	100	3	–	–	–	–	497	6
737B	1	25	6	50	8	25	10	559	1
7LW Concrete									
909B	4	100	2	–	–	–	–	493	39
905B	4	50	2	25	1[c]	–	–	493	37
904B	4	25	2	50	1[c]	–	–	493	35
457C	4	100	1[d]	–	–	–	–	475	34
908B	2	50	4	25	1	–	–	526	30
906B	2	100	2	–	–	–	–	515	29
985B	1	50	7	–	–	–	–	502	7
129C	1	100	2	–	–	–	–	638	2

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] This specimen was placed in a fourth exposure of 50% RH for four cycles.

[c] The last cycle was incomplete at the conclusion of the study.

[d] This specimen was cured for 231 days in 100% RH prior to being encased in a permeameter, and the first cycle was incomplete at the conclusion of the study.

GENERAL DISCUSSION

For all concretes, the effects of specimen thickness on permeability seem to be fairly well defined in all exposures except in 100% RH. The consistent trend is that the thicker the specimen, the longer the cycle time. From an analytical standpoint, these results in a drying exposure seem reasonable, because the slope of the humidity gradient in the thicker specimens would be less steep than in the thinner ones. Other things being equal, this means that the zone of higher internal humidity will be greater in the thicker specimens, thus reducing the effective vapor pressure difference from upper to lower face to less than that of a similar thinner specimen. The lower vapor pressure difference, in turn, means lower "driving force" on the water and consequently longer cycle time. The longer lengths of paths of water flow in thicker specimens also mean more friction to overcome and slower movement. In addition, continuing cement hydration within the mass results in a constantly changing matrix.

Perhaps one could say that the specimens with the lower face exposed to 100% RH were virtually saturated, since the concrete was exposed to 100% RH on both upper and lower faces. Assuming this were true, there would still be a difference in rate of flow due to higher friction in thicker specimens even after steady-state flow had been established. The erratic results in the 100% RH specimens indicate that it is highly unlikely that a state of laminar flow was reached in any of the 100% RH specimens in the time allotted to the study. There was a varying amount of drying of each specimen prior to its installation in a permeameter. Each specimen was removed from 100% RH curing at age 14 days and than sealed in a permeameter as soon as possible. There were unavoidable delays in the sealing process which allowed the surfaces of the specimens to partially dry. In some cases, the initial inflow of water from the standpipe served to replace the lost water in the upper portion of the specimens. The differences in degree of drying from specimen to specimen may account for the differences in cycle time for the first cycle.

The effects of concrete type on permeability are summarized in Table 22. As stated before, 7LW concrete appears to have been the most impermeable, but since there are basic differences in the mixes, a relative comparison may be invalid. It may suffice to say that normal-weight thin-shell concrete can be made fairly watertight by using a relatively low W/C and that thin-shell concrete made with expanded shale coarse and fine aggregate can also be made relatively watertight. In general, the test results show that the wetter the exposure condition at the lower face, the longer it will take for water to move through the concrete. When this trend did not hold true, usually only one specimen had been used for a given thickness and exposure.

An existing thin-shell concrete roof would be subjected to periods of drying as well as to periods of precipitation. It seems highly unlikely that water would be allowed to stand on a roof for the periods indicated in this study to be necessary to establish an ultimate value for resistance to water passage. During the periods of dry weather, the concrete roof would be drying from both sides. When precipitation did occur, the concrete, if unprotected, would absorb water quite readily, but as shown in these tests, the water would come from the underside in vapor form, unless there was a crack to provide a path for liquid water. Even with a high vapor pressure difference between faces (25% RH on lower face), the water took a relatively long time to come from the lower face as a vapor. Only in specimens in which the lower face was exposed to 100% RH was liquid water found on the lower face.

An attempt was made to obtain meaningful coefficients using the equation originated by Darcy and adapted for falling-head permeability by Lorman.[10] The equation is

$$K = \frac{a\,t \log_e (h_1/h_2)}{A\,T}$$

where K = coefficient of permeability (in./day)

a = cross-sectional area of standpipe (0.048 in.^{2})

t = thickness of test specimen (in.)

h_1 = standpipe water head at beginning of cycle (16 in.)

h_2 = standpipe water head at end of cycle (4 in.)

A = cross-sectional area of test specimen (26.057 in.^{2})

T = time required for water level to drop from h_1 to h_2 (days)

Results of computations with the above equation using data on 8.25NW specimens from Tables 2, 3, and 4 are shown in Table 24. Formulation of the equation was based on an assumption of laminar (steady-state) flow of water through the concrete. In the study reported here, if this flow condition existed, it was in specimens with the lower face exposed to 100% RH. In Table 24 the coefficients for 100% RH exposure seem to indicate that more water passed through specimens 4 inches thick in 1 day than through the thinner ones. This is refuted by cycle-time test data in Tables 2, 3, and 4.

Table 24. Coefficients of Permeability for 8.25NW Concrete Specimens

Relative Humidity of First Exposure (%)	Average Coefficient of Permeability (K) and Cycles Completed for Specimens—					
	1 Inch Thick		2 Inches Thick		4 Inches Thick	
	K (in./day x 10^{-6})	Cycles[a]	K (in./day x 10^{-6})	Cycles	K (in./day x 10^{-6})	Cycles
25	116	3	176	3	189	3
70	90	3	165	3	255	3
100	16	1	47	1	85	1

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Since water flow through specimens with lower faces exposed to 25% RH and 70% RH was assuredly not laminar, coefficients of permeability computed with the above equation would be suspect. The coefficients in Table 24 for these specimens show the same qualitative thickness effects as noted with the 100% RH specimens. As before, the test data in Tables 2, 3, and 4 refute such relationships. It is interesting to note in Table 24 that if attention is given to one specimen thickness at a time, the relationship vertically in the table is reasonable except for the 4-inch-thick specimens exposed to 70% RH.

The author believes that the basic weaknesses in the above equation when used on concrete are twofold: (1) The assumption of laminar flow is erroneous, and (2) the equation assumes only one mode of water movement—direct flow as a liquid. The equation was developed for soils and cannot account for the several modes of water movement in concrete caused by the unique gellike matrix, which is constantly changing due to continuing hydration of cement.[10] In addition, size of member (ratio of surface area to volume) has been found to have a significant effect upon shrinkage and creep, which are also a function of water movement in concrete.[5,18]

FINDINGS

1. The permeability of both normal-weight and lightweight concrete is a function of the difference in humidity between upper and lower faces of the concrete (vapor-pressure difference); the greater the difference in humidity, the higher the permeability (the faster water will pass through).

2. In specimens in which the lower face was exposed to a drying environment, water came from the concrete as a vapor. Only in those specimens exposed to 100% RH at the lower face did water appear at the lower face as a liquid.

3. In specimens exposed to drying at the lower face, the thicker the specimens, the slower the rate of water passage.

4. 8.25NW concrete was less permeable than 6.5SLW concrete and more permeable than 7LW concrete.

5. The permeability of 6.5NW concrete was not significantly different from that of 8.25NW concrete.

6. The highest percentages of zinc oxidation from the galvanized mesh occurred in the least permeable concrete, 7LW lightweight.

7. The lowest percentages of zinc oxidation occurred in 8.25NW concrete.

8. Treatment with boiled linseed oil reduced permeability to between 1/5 and 1/8 of the permeability of untreated specimens for this particular test method.

9. Reliability of the equation for coefficient of permeability (falling head) could not be verified.

CONCLUSIONS

1. In typical thin-shell concrete roofs, the thicker the concrete, the slower water will penetrate the concrete.

2. For a given concrete, the greater the humidity difference between concrete faces, the greater the difference in vapor pressure and the faster the rate of water passage.

3. From the standpoint of resistance to water passage, any of the concretes used in this study would make a satisfactory thin-shell concrete roof, if the concrete is properly poured and cured, because the probability of long-standing water on a roof is unlikely.

RECOMMENDATIONS

Since the concrete itself can be made satisfactorily resistant to water passage if proper inspection and control are maintained during construction, cracks are the most significant source of water leakage through thin-shell

concrete roofs. It is therefore recommended that studies be undertaken to develop processes or methods by which cracking can be eliminated or inhibited. Overcoming effects of tensile stresses with compressive stresses induced by expansive concrete may be one solution but, at present, little has been done to determine the amount of expansion obtainable when mesh reinforcement is used.

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Appendix A

DETAILS OF CONCRETE MIXES

Pertinent data on the concrete mixes are shown in Table A-1. The batches were made in a pan-type laboratory mixer in quantities of 1.4 to 1.5 ft^3. Mixing procedures for the mixes are given below.

8.25NW and 6.5NW Concrete

1. Mix aggregate and cement dry for 30 seconds.
2. Add water and mix for 2-1/2 minutes.
3. Measure slump and add water if necessary.

6.5SLW Concrete

1. Soak coarse aggregate (expanded shale) for 10 minutes in about 2/3 of the mixing water.
2. Add fine aggregate and air-entraining agent.
3. Mix for 30 seconds.
4. Add cement and remainder of mixing water.
5. Mix for 3 minutes.
6. Let concrete stand for 5 minutes.
7. Remix for 10 seconds.
8. Measure air content and slump and add water if needed.

7LW Concrete

1. Soak coarse aggregate (expanded-shale) for 3 minutes in about 2/3 of mixing water.
2. Add expanded-shale sand and soak for 10 minutes.
3. Add air-entraining agent and mix for 30 seconds.
4. Add cement and remainder of mixing water and mix for 3 minutes.
5. Let concrete stand for 5 minutes.
6. Remix for 10 seconds.
7. Measure air content and slump and add water if needed.

Table A-1. Material Requirements for Concrete Mixes

Item	Concrete Mix			
	8.25NW	6.5NW	6.5SLW	7LW
Coarse aggregate	1,270 lb 3/8-in. minus Santa Clara River gravel	1,335 lb 3/8-in. minus Santa Clara River gravel	738 lb 3/8-in. minus expanded shale	720 lb 3/8-in. minus expanded shale
Fine aggregate	1,620 lb Santa Clara River sand	1,700 lb Santa Clara River sand	1,278 lb Santa Clara River sand	845 lb expanded shale sand
Cement, type III	775 lb (= 8.25 sacks)	611 lb (= 6.5 sacks)	611 lb (= 6.5 sacks)	658 lb (= 7 sacks)
Water	343 lb (≈ 41 gal)	334 lb (= 40 ± 1/2 gal)	330 lb (= 40 ± 1/2 gal)	338 lb (= 40 ± 1/2 gal)
Air-entraining agent (neutralized vinsol liquid resin as supplied by manufacturer)	none	none	162 ml	207 ml
Average air content	not measured	not measured	5.3%	5.4%
W/C ratio	0.44 (≈ 5 gal/sack)	0.55 (≈ 6.2 gal/sack)	0.53 (≈ 6 gal/sack)	0.51 (≈ 5.7 gal/sack)
Slump	3 in.	3 in.	3 in.	3 in.
Unit weight (wet)	148 pcf	147 pcf	112 pcf	99 pcf
Compressive strength (3 x 6-in. cycle at 14 days)	6,220 psi	5,810 psi	5,490 psi	5,580 psi

Appendix B

MISCELLANEOUS TESTS

Permeability tests were made on a few specimens of concrete containing (1) an expansive cement and (2) type II portland cement rather than type III.

Expansive Cement Concretes

The limited research program for concretes made with a shrinkage-compensating expansive cement, rather than with portland type III cement, is shown in Table B-1. The expansive cement utilizes the restraint of formwork and of reinforcing steel to induce compressive stresses into the concrete during setting and hardening. It was thought that the compressive strains caused by the induced stresses might tend to reduce the pore sizes in the concrete matrix and thus reduc permeability.

Tests on 8.25NW-E Concrete. Results are shown in Table B-2. Comparisons with 8.25NW concrete are presented in Table B-3. For the limited data shown, use of the expansive cement seems to have increased rather than reduced the permeability. It is quite possible that there was insufficient restraint to develop the full value of the expansive characteristics of the cement; the reinforcement percentages were 0.53% for the 1-inch specimens and 0.38% for the 2-inch and 4-inch specimens.

Tests on 6.5SLW-E Concrete. Results are presented in Table B-4. Comparisons with tests made on 6.5SLW are shown in Table B-5. For the data shown, the expansive cement offers no advantage regarding permeability.

Concretes Made With Portland Type II Cement

The limited research program for concretes utilizing portland type II cement rather than type III is shown in Table B-6. It was desired to determine the relative effects on permeability of the coarser grind of the type II. In addition, type II portland cement generates heat at a slower rate (due to lower tricalcium aluminate content), and concretes made with this cement are especially resistant to soils and water containing alkalis[19] and thus might also be more impermeable than concrete made with type III cement. To approximate the same compressive strength and state of hydration at time of installation, the specimens utilizing type II cement were encased in permeameters when 28 days old rather than when 14 days old, as were the specimens of the other concretes.

Table B-1. Experimental Program for Concretes Made With Expansive Cement

(All specimens 2 inches thick.)

Type of Concrete	First Lower Face Exposure		Second Lower Face Exposure	
	Relative Humidity (%)	Cycles[a]	Relative Humidity (%)	Cycles
8.25NW-E	25	13	50	7
	50	10	25	8
	100	3	–	–
6.5SLW-E	25	10	50	4
	50	14	–	–
	100	4	–	–

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Tests Made on 8.25NW-II Concrete. Results of tests with concrete identical to 8.25NW except that portland type II was used are presented in Table B-7. Comparisons with tests made on 8.25NW concrete are shown in Table B-8. Meager though they are, the trends seem to indicate that the type II cement may indeed contribute to lower permeability.

Tests Made With 6.5SLW-II Concrete. Results are shown in Table B-9. Comparisons with tests made on specimens of 6.5SLW concrete are presented in Table B-10. Contrary to results shown for normal-weight concrete, the type II cement seems to offer no improvement in impermeability.

Tests Made With 7LW-II Concrete. Test results are presented in Table B-11. Comparisons with tests made on 7LW concrete are presented in Table B-12. Use of type II cement does not seem to offer any advantages over type III in reducing permeability.

Table B-2. Days Per Cycle[a] for 8.25NW-E Concrete (Expansive Cement), Specimens 2 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
398C	25	4.25	9.25	9.75	13.00	13.50	14.00	14.00	14.25	14.50	16.00	15.25	15.25	16.00							
	50														21.75	21.25	21.25	22.00	22.50	22.75	23.25
399C	50	7.00	9.25	14.00	15.50	17.50	19.00	20.00	22.25	22.25	22.00										
	25											19.00	18.25	18.25	18.75	20.00	19.25	20.50	21.00		
400C	100	21.25	65.00	[illegible]																	

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table B-3. Comparison of 8.25NW and 8.25NW-E Concrete Mixes

(Specimens 2 inches thick.)

Relative Humidity of First Exposure (%)	Days Per Cycle and Number of Cycles for Concretes—			
	8.25NW		8.25NW-E	
	Days	Cycles[a]	Days	Cycles
25	22.50	4	13.00	4
25	39.00	4	–	–
25	35.50	4	–	–
50	37.75	5	17.50	5
100	204.75	2	65.00	2

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table B-4. Days Per Cycle[a] for 6.5SLW-E Concrete (Expansive Cement), Specimens 2 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
523C	25	4.75	10.00	13.25	15.00	16.75	17.50	18.75	20.50	21.00	22.75				
	50											31.25	34.25	37.25	39.25
524C	50	6.00	10.75	13.75	16.75	19.00	20.75	23.00	24.50	25.50	29.00	29.00	30.50	32.50	34.50
525C	100	7.75	27.25	94.25	188.75										

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table B-5. Comparison of 6.5SLW and 6.5SLW-E Concrete Mixes

(Specimens 2 inches thick.)

Relative Humidity of First Exposure (%)	Days Per Cycle and Number of Cycles for Concretes—			
	6.5SLW		6.5SLW-E	
	Days	Cycles[a]	Days	Cycles
25	18.25	9	21.00	9
	27.75	9		
	19.50	9		
50	31.50	5	19.00	5
	34.25	5		
	36.25	5		
100	247.00	2	27.25	2

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table B-6. Experimental Program for Concretes Made With Type II Portland Cement

Specimen Thickness (in.)	Relative Humidity Lower Face Exposed to and Number of Cycles	
	RH (%)	Cycles[a]
8.25NW-II Concrete		
2	25	4
2	50	3
2	100	1[b]
6.5SLW-II Concrete		
1	25	11
1	50	9
1	100	2
7LW-II Concrete		
1	25	5
1	50	4
1	100	1

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] The first cycle was not completed; water level was 5.30 inches after 194 days. The curve was extrapolated to estimate the completed cycle of 274 days.

Table B-7. Days Per Cycle[a] for 8.25NW-II Concrete (Type II Portland Cement), Specimens 2 Inches Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—			
		1	2	3	4
880C	25	33.25	38.00	42.50	45.25
881C	50	36.00	45.75	55.75	
882C	100	274.00[b]			

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] Extrapolated to complete the cycle after 194 days of exposure.

Table B-8. Comparison of 8.25NW and 8.25NW-II Concrete Mixes

(Specimens 2 inches thick.)

Relative Humidity of First Exposure (%)	Days Per Cycle and Number of Cycles for Concretes—			
	8.25NW		8.25NW-II	
	Days	Cycles[a]	Days	Cycles
25	22.50	4	45.25	4
	39.00	4	–	–
	35.50	4	–	–
50	34.25	3	55.75	3
100	211.00	1	274.00	1[b]
	132.75	1	–	–
	70.00	1	–	–

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

[b] Extrapolated to estim[illegible] cycle.

Table B-9. Days Per Cycle[a] for 6.5SLW-II Concrete (Type II Portland Cement), Specimens 1 Inch Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—										
		1	2	3	4	5	6	7	8	9	10	11
900C	25	9.75	8.50	9.50	10.25	11.25	12.00	11.75	12.75	12.75	14.25	14.00
907C	50	10.50	11.25	12.50	14.00	15.50	16.50	17.75	17.75	18.75		
908C	100	54.75	118.50									

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table B-10. Comparison of 6.5SLW and 6.5SLW-II Concrete Mixes

(Specimens 1 inch thick.)

Relative Humidity of First Exposure (%)	Days Per Cycle and Number of Cycles for Concretes—			
	6.5SLW		6.5SLW-II	
	Days	Cycles[a]	Days	Cycles
25	24.00	5	11.25	5
	12.50	5	–	–
	15.00	5	–	–
50	16.00	7	17.75	7
100	195.25	2	118.50	2
	206.25	2	-	–
	111.50	2	–	–

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table B-11. Days Per Cycle[a] for 7LW-II Concrete (Type II Portland Cement), Specimens 1 Inch Thick

(Exposures at various humidities are sequentially grouped for each specimen.)

Specimen No.	Relative Humidity on Lower Face (%)	Days to Complete Cycle No.—				
		1	2	3	4	5
865C	25	19.50	23.50	29.00	33.50	38.50
866C	50	21.75	30.00	41.75	53.00	
867C	100	55.75				

[a] One cycle is the time in days required for water head to fall from 16 inches to 4 inches.

Table B-12. Comparison of 7LW and 7LW-II Concrete Mixes

(Specimens 1 inch thick.)

Relative Humidity of First Exposure (%)	Days Per Cycle and Number of Cycles for Concretes—			
	7LW		7LW-II	
	Days	Cycles[a]	Days	Cycles
25	37.75	5	38.50	5
	36.75	5	–	–
50	33.75	3	41.75	3
	42.75	3	–	–
	26.00	3	–	–
100	59.00	1	55.75	1
	55.75	1	–	–

[a] One cycle is time in days required for water head to fall from 16 inches to 4 inches.

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TR-692 54 p. illus August 1970 Unclassified

1. Reinforced thin-shell concrete I. YF 51.542.001.01.001

Falling-head permeability tests were conducted on specimens of two normal-weight concretes and two lightweight concretes typical of those used in thin-shell reinforced concrete roofs. Specimens of each concrete with galvanized mesh reinforcement were tested in thicknesses of 1 inch, 2 inches, and 4 inches. Initially, the upper face of each specimen was exposed to a 20-inch head of water. The lower faces of the specimens were initially exposed to relative humidities of 25%, 50%, 70%, or 100%, all at a constant temperature of 73.4°F. A lightweight concrete utilizing expanded shale for both coarse and fine aggregate was the least permeable of all the concrete tested. The degree of zinc oxidation from the mesh was determined for some of the specimens. The reliability of the equation for coefficient of permeability (falling head) could not be verified. Any of the concretes tested in this study could be used to make a relatively impermeable thin-shell concrete roof. Since the concrete itself can be made satisfactorily resistant to water passage, cracks are the most significant source of water leakage through thin-shell concrete roofs.

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